Fruit and Vegetable Flavor

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Introduction: The quality of fresh produce has traditionally been based on external characteristics of size, color, and absence of surface defects. Fruit and vegetable breeders selected for color, size, disease resistance, yield and other easily quantified horticultural traits. Because flavor and texture characteristics were not a part of the selection process, improvements in these quality attributes have not kept pace with the more easily quantified traits. Public and industry organizations are increasing concerned with the public's growing dissatisfaction over the flavor and texture of some horticultural produce.

Flavor and aroma are perhaps the most elusive and subjective of quality traits. Flavor is taste plus odor and is mainly composed of sweetness, sourness, and aroma, which corresponds to sugars, acids, and volatiles. Other components of flavor include bitterness, eg., related to sesquiterpene lactones in chicory (Peters and Amerongen, 1998), saltiness due to various natural salts, and astringency related to flavonoids, alkaloids (DeRovira, 1997), tannins (Taylor, 1993), and other factors. The perception of sweetness, ie., sugars, one of the most important components of fruit or vegetable flavor, is modified by sourness or acid levels, and aroma compounds. The contribution of aroma to the flavor quality of fresh produce has gained increasing attention.

Genetics is the primar determinant of flavor of fresh produce (Baldwin et al., 1991b and 1992; Cunningham et al., 1985), with pre-harvest environment (Romani et al., 1983), cultural practices (Wright and Harris, 1985), harvest maturity (Fellman et al., 1993; Maul et al., 1998; Baldwin et al., 1999a), and postharvest handling (Mattheis et al., 1995; Fellman et al., 1993; Baldwin et al., 1999a and b) having lesser effect. Fruit such as apples and bananas that continue to ripen after harvest are termed climacteric, while those such as citrus and strawberries that do not ripen after harvest are termed non-climacteric. The flavor quality of non-climacteric fruit generally declines after harvest, while climacteric fruit can reach their best flavor after harvested. Climacteric fruit develop better quality if harvested after the start of ripening, while fruit of both will be inferior quality if harvested immature, even if held under optimal postharvest conditions.

Human perception of flavor is exceedingly complex. Taste is the detection of nonvolatile compounds (in concentration of parts per hundred) by several types of receptors in the tongue for sugars or polyalcohols, hydronium ions, sodium ions, glucosides and alkaloids, etc. These correspond to the perception of sweet, sour, salty and bitter tastes in food. Aroma compounds can be detected in ppb concentrations and are detected by olfactory nerve endings in the nose (DeRovira, 1997). The brain processes information from these senses to give an integrated flavor experience. This integration makes it difficult to determine the relative importance of each input since the brain can interpret changes in aroma as changes in taste (O'Mahony, 1995) or vice versa. For example, the levels of aroma compounds influenced panelist perception of sweetness and sourness for tomatoes (*Lycopersicon esculentum* Mill.) (Baldwin et al., 1998). Conversely, levels of taste components influenced panelist perception of aromatic descriptors in mango (*Mangifera indica* L.) (Malundo et al. 2000a). The perception of certain combinations of chemicals is synergistic, while others combinations mute our perception in a process called masking. In contrast to masking, is anesthetization or blanking in which as olfactory receptors become overloaded. Lighter aroma volatiles, eg., top notes, low molecular weight, polar, hydrophilic compounds, are perceived first and generally have the major impact on perception, while heavier compounds are perceived later, eg., background. notes, high molecular weight, non-polar, hydrophobic compounds (DeRovira, 1997).

Sensory Evaluation: Human perception of flavor can be determined by sensory evaluation by taste panels. Consumer preference and acceptance varies due to socioeconomic, ethnic and geographical

background; often necessitating the segmenting of sub-populations for a particular study (O'Mahony, 1995). Generally large numbers, eg., 50 to 100, of panelists rank their perceptions on a traditional 9-point hedonic scale, but sometimes a simple 3-point scale including the descriptive terms outstanding, acceptable, and unacceptable can be effective for tomato fruit evaluation. In one study, adaptation of logistic regression from medical science proved useful, where a 0 or 1 indicates whether the consumer would or would not purchase a mango (Mangifera indica). The consumer was asked to base their decision on flavor that was then related to chemical constituents (Malundo et al., 2000b). Difference testing can be used to measure slight differences between foods (usually due to one particular aspect of flavor), and is considered a narrow band approach. Descriptive analysis measures intensities of a set of sensory attributes and is considered a broadband approach (O'Mahony, 1995). Panelists are trained to detect a range of flavor attributes and score their intensity, generally on a 150 mm unstructured line. Sensory studies for fresh produce can be used to identify optimal harvest maturity, evaluate flavor quality in breeding programs, determine optimal storage and handling conditions, assess effects of disinfestation or preconditioning techniques on flavor quality, and measure flavor quality over the postharvest life of a product.

Taste Components: Fructose, sucrose, and glucose are the sugars that affect the perception of sweetness in fruits and vegetables. Fructose is the sweetest, and glucose as less sweet than sucrose. A single "sucrose equivalent" value is the weighed average of these various sugars a sample (Koehler and Kays, 1991). Sugar content is commonly accepted to be synonymous with SSC, and an inexpensive refractometer can easily measure SSC. However, the quantification of individual sugars requires complicated laboratory analysis. Breeders often select for higher SSC in an attempt to increase sweetness. In some fruits, such as orange (*Citrus sinensis*), SSC relates to sweetness, while in others, like tomato and mango, the relationship is not linear (Baldwin et al., 1998 and 1999a; Malundo, et al. 2000a).

Organic acids, such as citrate in citrus and tomatoes, tartaric acid in grapes (*Vitis* sp.), and malic acid in apples (*Malus pumila*), give fruit and vegetables their sour flavor. Some fruits, like melon (*Cucumis melo*) or banana (*Musa* sp.), have very little acid (Wyllie et al., 1995). Different acids can affect sourness perception depending on their chemical structure. An increase in carboxyl groups decreased acidity, while an increase in molecular weight or hydrophobicity increased sourness (Hartwig and McDaniel, 1995). For example, acetate was perceived as more intensely sour than lactic or citrate.

Acids can be measured individually by HPLC (Baldwin et al., 1991a and b), by titration (TA) with sodium hydroxide (Jones and Scott, 1984), or by pH (Baldwin et al., 1998). Sometimes SSC, the ratio of SSC/TA, or pH relate better to sourness than TA itself (Baldwin et al., 1998; Malundo et al., 2000a).

Aroma Components: Volatiles that we can perceive contribute to food flavor. The level at which a compound can be detected by smell (the odor thresholds) can be established in a background similar to a food medium as described by the Ascending Method of Limits of the American Society for Testing and Materials (ASTM, 1991). Log odor units are calculated from the ratio of the concentration of a component in a food to its odor threshold. Compounds with positive odor units contribute to food flavor. Buttery (1993), for example, determined concentrations, odor thresholds and log odor units for those tomato volatiles present at levels of one ppb or more (about 30 of > 400 identified compounds). However, the aroma perception of volatile compounds is affected by the medium of evaluation. For example, both the thresholds and descriptors of some volatile compounds in tomato were different if the background media contained levels of methanol and ethanol similar to that found in fresh tomato homogenate or in deodorized homogenate itself, compared to water (Tandon et al.. 2000) (Table 1).

Aroma compounds are often only released upon cell disruption when previously compartmentalized enzymes and substrates interact (Buttery, 1993). Some aroma compounds are bound to sugars as glycosides (celery [*Apium graveolens*], lettuce [*Lactuca sativa*]), or glucosinolates (cabbage [*Brassica oleracea*], radish [*Raphanus sativus*]). This linkage can be cleaved by enzyme action or heat during cooking. Others are breakdown products of lipids, amino acids, lignin, or pigments (Buttery and Ling,

1993).

Measurement of aroma compounds is difficult and time consuming. Earlier studies employed the classical flavor isolation procedures of steam distillation and/or solvent extraction (Teranishi and Kint, 1993). The disadvantage of this method is that it can qualitatively and quantitatively modify the flavor profile of a sample (Schamp and Dirinck, 1982). This method is not easily applied to large numbers of samples, and internal standards must be incorporated to determine recovery. The resulting concentration of material, however, allows identification of compounds by gas chromatography-mass spectrometry (GC-MS). More recently, investigators have employed purge and trap headspace sampling methods which involve trapping and concentrating volatile components on a solid support. Volatiles are later released from the trap using heat for analysis by GC-MS. This method is excellent for quantification and identification of aroma compounds (Teranishi and Kint, 1993; Schamp and Dirinck,, 1982.

Static headspace methods are said to more closely reflect the true flavor profile, but compounds are present at low levels, and some may not be detected. Cryofocusing (cold trap) of static headspace volatiles (Teranishsi and Kint, 1993) reduces this problem since samples are concentrated without heating that may cause adulteration. This method has been used for quantification of orange juice volatiles (Moshonas and Shaw, 1997). The newest method is solid phase micro extraction (SPME), a rapid sampling technique where volatiles interact with a fiber-coated probe inserted into the sample headspace. The probe is then transferred to a GC injection port where the volatiles are desorbed. It has been used on apples, tomatoes (Song et al., 1997) and strawberries (Golaszewski et al., 1998; Song et al., 1997).

Aside from GC and GC-MS methods, there are new sensors available that have a broad range of selectivity. These sensor arrays, called "electronic noses," are useful to discriminate among samples based on the interaction of volatile components with the various sensors. The resulting response pattern allows a particular sample or flavor component(s) to be detected by pattern recognition. However, these instruments do not give information that leads to identification/quantification of individual compounds. Four basic sensor technologies have been commercialized to date. Metal oxide semiconductors (MOS), metal oxide semiconductor field effect transistors (MOSFET), conducting organic polymers (CP), piezoelectric crystals (bulk acoustic wave, BAW) or quartz crystal microbalance. Such sensors are divided into two classes since they either operate "hot" (MOS, MOSFET) or cold (CP, BAW). The "hot" sensors are less sensitive to moisture and have less carry-over from one measurement to the next. The next generation of electronic noses may employ fiberoptic, electrochemical and bi-metal sensors that are currently under development (Schaller et al., 1998).

Relating Sensory to Chemical Data: Chemical analysis of flavor compounds provides little insight into the actual flavor experience. However, sensory attributes, preferences, and decisions can be statistically related to chemical components in foods (Martens et al., 1994). Correlation of physical measurements with sensory analysis gives meaning to instrumental data; as was shown with apple and tomato (Baldwin et al., 1998). For example, linear regression established relationships between levels of sesquiterpene lactones and bitterness in chicory (Peters and Amerongen, 1998). Multivariate methods require large data sets, but non-linear regression techniques such as principle component or discriminate analysis yielded useful results for citrus (Moshonas and Shaw, 1997), strawberry (*Fragaria ananassa*) (Shamaila et al., 1992), and tomato (Maul et al., 1998). Differences between samples were found based on measurement of volatiles or other flavor compounds. Alternatively, sniff ports (olfactometry detectors) can be used with GCs, allowing a person to determine if odors are detectable as well as their relative intensity as the volatile components are separated by the GC column. This technique was used on apples (Cunningham et al., 1985; Young et al., 1996). Descriptive terms can be assigned to the respective peaks on the GC chromatogram that have odor activity (Acree, 1993). The drawback to this method is that the interactive effects of volatile compounds with each other and with sugars and acids, both chemically and in terms of human perception, are eliminated.

Factors that can Effect Flavor of Fruits and Vegetables:

Effect of genetics on flavor

Fruit and vegetable varieties differ in flavor based on sensory and chemical analysis. "Charm" analysis combines separation on a GC column with a sniff port to assign biological activity (odor activity) to individual aroma components as they are identified and quantified by GC (Cunningham et al., 1985). This study with 40 cultivars showed that apple aroma was not the result of the same compounds in every cultivar, although some common volatile compounds were important in all cultivars.

Important aroma-specific compounds for strawberry included ethyl butanoate, methyl butanoate, gamma-decalactone, and 2-heptanone (Larsen et al., 1992). Strawberry cultivars differed in flavor intensity and sweetness according to a trained sensory panel (Podoski et al., 1997). Concentrations of several important compounds including α- and ß-ionones, were higher in wild compared to cultivated raspberries (*Rubus* sp.). In addition, numerous aroma compounds were found only in wild berries, all of which may contribute to the stronger and more pleasant aroma of wild berries (Martin and MacLeod, 1990). In tomato, the TA/SSC (Stevens et al., 1977) and levels of flavor volatiles varied significantly among varieties (Baldwin et al., 1991a and b). Insertion of the *rin* gene to reduce ethylene production and slow tomato fruit softening, resulted in some deterioration in flavor quality (Baldwin et al., 2000) and reduction in flavor volatiles (Baldwin et al., 1992; Baldwin et al., 2000). Flavor appears to be related to ethylene production (Baldwin et al., 1991a and 2000). Transgenic fruit with antisense aminocyclopropanecarboxylic acid (ACC) synthase (enzyme in the ethylene biosynthetic pathway) had lowered levels of many important flavor volatiles (Baldwin et al., 2000). Fruit with antisense pectinmethylesterase (demethylates pectin in cell walls) had lowered levels of methanol, while those with downregulated phytoene synthase (phytoene is a precursor of carotenoids) had lowered levels of carotenoid-derived volatiles (Baldwin et al., 2000).

Effect of Pre-harvest Factors

Pre-harvest factors such as sunlight, water availability, fertilization, and chemical applications affect crop growth, and can affect internal quality characteristics of the harvested product, including flavor. Pre-harvest treatment with aminoethoxyvinylglycine (AVG) suppressed volatile production in pears by 50%, which was reversed by ethylene exposure (Romani et al., 1983), and heavy rains prior to harvest dilute flavor compounds in tomato. Fruit from tomato plants treated with increased levels of N and K fertilizer scored lower in sensory analysis, and showed increased levels of TA, SSC, and several volatiles (Wright and Harris, 1985). Pre-harvest mite control resulted in sweeter and more flavorful field grown strawberries than those receiving no treatments, according to a trained sensory panel (Podoski et al., 1997).

Effect of Harvest Maturity

Horticultural crops should be harvested at optimal eating quality, but practical considerations after dictate that they are harvested at a stage that minimize physical damage during shipping and handling, and maximizes shelf life. The climacteric stage at harvest affected ester formation in apples (Fellman et al., 1993). Harvest maturity affected both the sensory and chemical analysis of ripened tomato fruit (Maul et al., 1998). Tomatoes harvested at the immature green stage resulted in ripened fruit with lower volatile levels than mature green-harvested tomatoes. Harvest maturity also affected consumer acceptability ratings for mango, and trained descriptive panel ratings for sweetness, sourness, and various aroma descriptors. Fruit harvested later were sweeter, less sour and generally had more intense aroma characteristics (Baldwin et al., 1999a).

Effect of Postharvest Handling

Various techniques are used to extend the shelf-life of fruits and vegetables after harvest, to control postharvest decay, and to eliminate pests (quarantine treatments). These storage techniques and treatments involve cold, heat, irradiation, chemical applications, and different storage atmospheres.

Tomato fruit stored at 36, 41, 50, and 55 °F (2, 5, 10, and 13 °C) had reduced levels of important

volatiles and had less ripe aroma and flavor as well as more off-flavor compared to fruit stored at 68 °F (20 °C), as quantified by a trained descriptive panel (Maul et al., 2000). Subjection of fruit to heat treatments for pre-conditioning and decay control (McDonald et al., 1996), resulted in altered aroma volatile profiles. Heat treatment of apples to reduce physiological and pathological disorders inhibited emission of volatile esters important to apple flavor (Fallik et al., 1997). Levels of fructose and glucose, but not sucrose, decreased with increased storage time and storage temperature for muskmelon. However, sensory analysis did not find differences in flavor or sweetness between stored and freshly harvested melons (Cohen and Hicks, 1986).

CA storage altered flavor of apples, and if prolonged, reduced volatile emission compared to air-stored fruit, especially lipid-derived esters (Mattheis et al., 1995). Low O_2 storage decreased ester content and the enzymatic activity responsible for ester biosynthesis in apples (Fellman et al., 1993). However, when atmospheres induced anaerobic metabolism, large concentrations of ethanol and acetaldehyde accumulated. The altered synthesis of fruit volatiles resulted in increased amounts of ethyl acetate and certain ethyl esters at the expense of others. Sensory analysis of CA-stored apples revealed that intensity of fruity and floral descriptors decreased after 10 weeks in CA, while sourness and astringency were higher compared to apples stored in air. CA storage also increased certain volatiles in tomato, compared to air-stored fruit (Crouzet et al., 1986).

Use of packaging and edible coatings can create a modified atmosphere (MA) with reduced O_2 and elevated CO_2 levels, similar to that of CA. Lowering O_2 and raising CO_2 can maintain the quality of many fresh fruits and vegetables for extended periods. However, exposure of fresh produce to O_2 levels below their tolerance level can increase anaerobic respiration and lead to the development of off-flavor. Use of edible coatings affects flavor and the level of volatile flavor compounds in citrus (Cohen et al., 1990), apple (Saftner et al., 1999) and mango fruit (Baldwin et al., 1999b). The coating barrier probably induced anaerobic respiration and the synthesis of ethanol and acetaldehyde, and entrapped volatiles, including ethanol and acetaldehyde (Baldwin et al., 1999b). In broccoli, sulfur-containing volatiles, including methanethiol and dimethyl disulfide, are produced in response to anaerobic conditions that can be created by MAP (Dan et al., 1997). Storing strawberries in MAP altered volatile profiles depending on conditions (CO_2, mixed gases, or air), enabling separation of the samples using multivariate statistics (Shamaila et al., 1992). Fruit treated with CO_2 had the greatest change in volatile levels. This was confirmed by another study where strawberry fruit stored in a CO_2 saturated atmosphere exhibited significant changes in volatile levels and phenylalanine ammonia lyase (PAL) activity (Dourtoglou et al., 1995). The amino acid phenylalanine is the precursor to a number of volatiles through a pathway for which PAL is the key enzyme.

In addition to CA, other gaseous treatments of fruits and vegetable have been reported. Use of ethylene to synchronize ripening has been practiced for years on banana and tomato, and for degreening of citrus. Ethylene gassing of tomato fruit alters volatile levels (McDonald et al., 1996). Treatment of apple fruit with 1-methylcyclopropene (1-MCP) and methyl jasmonate inhibited both ethylene production and production of many volatile alcohols and esters, including the formation of esters from alcohols (Fan and Mattheis, 1999). Treatment of bananas with 1-MCP also suppressed volatile production and composition, resulting in an increase in alcohols and a decrease in related esters (Golding et al., 1999). Application of acetaldehyde and ethanol vapors to blueberries, tomatoes and pears increased their sugar content, sugar-acid ratio, and hedonic sensory rating (Paz et al., 1981).

Other chemical treatments of fresh produce may also affect flavor. For example, pressure infiltration of apples with calcium chloride transiently reduced levels of important flavor volatiles (Saftner et al., 1999).

Flavor of some Popular Fruits and Vegetables:
Apple
Sucrose is the major sugar in apples, although it is slowly hydrolyzed to glucose and fructose during latter ripening stages. The major organic acid is malate, although some citrate is also present (Knee, 1993).

Eleven aroma compounds contributed to apple aroma in most of 40 cultivars, while 27 other compounds contributing to flavor where found only in certain genetic types (Cunningham et al., 1985). Loss of apple flavor after long term CA storage is a major problem, probably due to the reduction of volatile synthesis during storage (Mattheis et al.1995).

Peach (Prunus persica)
The main sugar in peaches is sucrose, but cultivars differ greatly in glucose:fructose:sorbitol ratios which may contribute to differences in flavor. The major organic acids are malate and citrate, with malate levels declining and citrate levels increasing as fruit ripen (Brady, 1993). Aroma of peaches and nectarines is distinguished by the presence of gamma- and delta-lactones (peach-like and coconut-like, respectively), although other esters and aldehydes contribute to peach flavor (Do et al., 1969; Crouzet et al., 1990). γ-Lactones from C-5 to C-12, γ-lactones and unsaturated lactones represent over 25% of the volatiles, with γ-lactone being the second most abundant component after benzaldehyde. γ-Undecalactone, although rarely reported in natural extracts, has a distinct peach odor. It has been named 'peach aldehyde,' and is used in peach flavor formulations (Crouzet et al., 1990). Ethyl hexanoate and 3-methylbutanoate, linalool, α-terpineol, 6-pentyl-α-pyrone (coconut odor) and benzyl alcohol are also considered important (Crouzet et al., 1990).

Small Fruits
Strawberry: In most berry fruits sucrose, glucose and fructose are present in roughly equivalent concentrations (Manning, 1993), and citrate is the major organic acid. Over 200 volatile compounds have been identified in strawberry. C-6 aldehydes such as hexanal and trans-2-hexenal are found, as well as lipoxygenase and hydroperoxide lyase. Lipoxygenase acts on linolenic acid to form 13- and 9-hydroperoxides which are cleaved by hydroperoxide lyase to form hexanal and cis-3-hexenal. The cis-3 hexenal is then isomerized to trans-2-hexenal (Perez et al., 1999), as was reported for tomato (Galliard, et al., 1977; Riley et al., 1996). 2,5-Dimethyl-4-hydroxy-3(2H)-furanone (furaneol) and its methyl ether (mesifuran) are important aroma components in both strawberry and tomato and are considered to be glycosidically bound in both fruits (Roscher et al., 1997). Of over 100 volatile compounds identified from strawberry, furaneol, ethyl hexanoate, and ethyl butanoate are considered to be the character impact compounds (Zabetakis and Holden, 1997). Sensory analysis of strawberry juice showed that furaneol was positively related to fresh flavor and negatively related to off-flavor, while α-terpineol was inversely related to fresh flavor (Golaszewski et al., 1998).
Raspberry (*Rubus idaeus, ursinus*): The main sugars in raspberry are sucrose, glucose and fructose with citric as the major organic acid (Robbins and Fellman, 1993). At least 200 volatile compounds have been identified in raspberry (Honkanen and Hirvi, 1990;, Dourtoglou et al., 1995). Impact flavor compounds for raspberry are 1-(p-hydroxyphenyl)-3-butanone, cis-3-hexenol, α- and β-ionones, α-irone and mesifurane. Other abundant volatiles include geraniol, nerol, and linalool among others (Paterson et al., 1993). The "raspberry ketone" or character impact volatile for raspberry is 4-(4-hydroxyphenyl)-butan-2-one (Larsen and Poll, 1990). It had the lowest threshold (therefore, having the largest contribution to flavor) followed by α-ionone, β-ionone, geraniol, linalool, and benzyl alcohol. Furaneol, linalool, and ethyl hexanoate were important general aroma compounds while ethyl butanoate, methyl butanoate, γ-decalactone and 2-heptanone were important cultivar-specific compounds (Larsen et al., 1992). The most potent flavor compounds identified using a retronasal aroma simulator in raspberries were β-damascenone, diacetyl, 1-hexen-3-one, 1-nonen-3-one, 1-octen-3-one, and cis-3-hexenal (Roberts and Acree, 1996).
Blackberry (*Rubus laciniata*): Fresh blackberry fruit contain 245 aroma compounds (Georgilopoulos and Gallois, 1987). The most abundant were heptan-2-ol, para-cymen-8-ol, heptan-2-one, hexanol, α-terpineol, pulegone, octanol, isoborneol, mytenol, 4-terpineol, carvone, elemincine, and nonanol. Although heptan-2-ol is an important flavor compound with an intense fruit taste with herbaceous nuances, no single volatile was identified as blackberry-like (Marton and MacLeod, 1990). Some

compounds in blackberry fruit and leaves are glycosidically bound such as benzyl alcohol, benzoic acid, 3-hydroxy-7,8-dihydro-β-ionol, and cis-3-hexenol among others (Humpf and Schreier, 1991).

Blueberry (genus *Vaccinium*): Blueberries have glucose and fructose as their major sugars and citric, malic and quinic acids (Eck, 1986). The odor impact compounds for high-bush blueberry (*Vaccinium myrtillus*) are trans-2-hexenal, trans-2-hexenol, and linalool, but also include geraniol, citronellol, hydroxycitronellol, farnesol and farnesyl acetate. Most volatiles are present below their threshold concentrations, but hydroxycitronellol was described by sensory panelists as blueberry-like. Rabbit-eye blueberries (*V. ashei*) have a different aroma thanhigh-bush. Some aroma volatiles unique to rabbit-eye blueberries include 1-penten-2-one, γ-terpinene, carveol, acetone, cis-caran-3-ol, ecineralone, α-cedrene, sabinol, geranyl formate, linalyl acetate, undecan-2-one, tridecan-2-one, ethyl acetate, ethyl tetradecanoate, dimethyl octanedioate, toluene, p-cymene, and β-ionone among others (Honkanen and Hirvi, 1990).

Grape (genus *Vitis*): Glucose and fructose are the predominant sugars in grapes, while tartaric and malic acids account for 90% of the TA (Kanellis and Roubelakis-Angelakis, 1993). Grapes show an increase in free and glycosylated aroma compounds at the end of ripening, after sugar accumulation has slowed (Coombe and McCarthy, 1997). This process is different from that of other berries and has been termed "engusting." The volatiles in wine grapes are the most complex and are classified into five groups, of which the first four have glycosylated forms: monoterpene (abundant in "floral" grapes), norisoprenoid, benzenoid, aliphatic and methoxypyrazine. The accumulation of flavor volatiles occurs late in the berry ripening cycle, well after accumulation of sugar as observed in Muscat berries (Park et al., 1991). Different varieties have distinctive aroma character. For example, Muscat odor is mainly composed of monoterpenes such as linalool and geraniol (Webb, 1981; Kanellis and Roubelakis-Angelakis, 1993). Carbernet Sauvignon, a *V. vinifera* cultivar, contains methoxyisobutylpyrazine, which has a strong, green bell pepper-like aroma (Webb, 1981). Benzyl and 2-phenylethyl alcohols, ethers, aldehydes, and hydrocarbons also contribute to aroma. American grapes (*V. labruscana and V. rotundifolia*) are not suitable for wine production because they possess what has been termed "foxy" and candy-like odors due to compounds like methyl anthranylate, aminoacetophenone, furaneol and methyl furaneol. ß-Phenylethanol, with its rose-like odor, was found to be important for muscadine (*V. rotundifolia*) aroma (Flora and Nakayama, 1981). The *V. vinifera* grapes exhibit a mild aroma that is more desirable for wine production (Shure and Acree, 1995).

Banana (genus Musa)

Sucrose is the predominant sugar in banana initially, but as ripening proceeds, glucose and fructose accumulate. Malic, citric and oxalic acids are the predominant organic acids with the astringent taste of unripe bananas being attributed in part to oxalate levels (Seymour, 1993). Characteristic aroma of bananas arises from a complex mixture of compounds including short-chain fatty acids such as acetates, butanoates, and 3-methylbutyl esters. Recently nonvolatile glycoside precursors were shown to release glycosidically bound volatiles from banana pulp by ß-glucosidase, including decan-1-ol, 2-phenylethanol, 3-oxy-pentanoic acid, 3-methylbutanoic acid and benzoic acid (Perez et al., 1997). Esters account for about 70% of the volatile compounds and acetates and butyrates predominate (Seymour, 1993). 3-Methylbutyl acetate, however, is considered to dominate banana flavor as the key odor-impact volatile (Berger, 1991) along with butanoate and 3-methylbutanoate (Engel et al., 1990). Unusual phenol derivatives, eugenol, 5-methoxyeugenol, eugenol-methylether, and elemicin contribute background notes for the full-bodied mellow aroma of ripe bananas (Engle et al., 1990).

Citrus

Sweet orange (*Citrus sinensis*): The major sugar in most citrus types is sucrose, with varying levels of glucose and fructose. The major acid is citrate. Typical orange aroma is attributed to alcohols, aldehydes, esters, hydrocarbons, ketones and other components of which over 200 have been identified. Of these, esters and aldehydes are the primary contributors followed by alcohols, ketones and

hydrocarbons (Bruemmer, 1975). There is no single impact compound for orange. However, octanal, decanal, nonanal, docecanal, ethylbutyrate, and limonene are likely contributors to flavor (Shaw and Wilson, 1980; Shaw, 1991).

Tangerine (*Citrus reticulata*): Analysis of tangerine essence revealed 34 volatile compounds that were odor contributors. However, no one compound was found to have a characteristic tangerine odor (Moshonas and Shaw, 1972). Later studies suggested that the compounds thymol and methyl-*N*-methylanthranilate (dimethylanthranilate) are odor impact compounds for this fruit, but that they are modified by the presence of monoterpene hydrocarbons. Nevertheless, dimethyl anthranilate is the most potent flavor component (Shaw and Wilson, 1980).

Grapefruit (Citrus paradisi): At least 126 volatile components have been identified in grapefruit (Demole et al., 1982). Nootkatone and 1-p-menthene-8-thiol may be key aroma impact compounds for grapefruit (Demole et al., 1982) although aldehydes and esters are also important (Shaw and Wilson, 1980).

Mango
The major sugars in mango (*Mangifera indica*) are glucose, fructose and sucrose, with sucrose predominating. The major acids are citric, malic, and sometimes tartaric at 0.1 to 0.4 % TA (Nairain, et al., 1997; Baldwin et al., 1999b,) and 10 to 16 SSC (Baldwin et al., 1999b). Mango varieties differ in amount and type of volatile compounds present (over 150 compounds identified), often depending on area of production. Asian mangoes have more oxygenated volatile compounds such as esters, furanones, and lactones, giving some varieties pineapple- or peach-like aromas (Narain et al., 1997), while Western mangoes that are hybrids of Asian stock have higher levels of certain hydrocarbons such as 3-carene (MacLeod and de Troconis, 1982; Wilson et al., 1986; Narain et al., 1997).

Pineapple (*Ananas comosus*)
Besides banana and possibly mango, pineapple is the most popular fruit from the tropics. SSC can range from 11 to 17° Brix, and the major sugars are glucose, fructose and sucrose, with sucrose predominating (Salunkhe and Desai, 1984; Shukor et al., 1998). The major acids are citrate and malate with about 0.1 to 0.6% titratable acidity (Salunkhe and Desai, 1984; Shukor et al., 1998). Over 120 volatiles have been identified in green and ripened pineapples with esters dominating at over 80% of the total volatiles (Shukor et al., 1998). Contributing aroma volatiles, based on odor thresholds show that pineapple aroma is also dominated by esters such as ethyl 2-methylbutanoate, ethyl acetate, ethyl hexanoate, ethyl butanoate, methyl heptanoate and others. Furaneol is also reported to be important (seems it is found in every fruit). Genetically engineered fruit with down- or up-regulated alcohol dehydrogenase expression exhibited altered levels of some related volatiles (Speirs et al., 1998).

Melons (*Cucumis melo*)
Sucrose is the principal sugar in most melon types, although high levels of fructose may be present in some watermelon cultivars. Melons contain citrate and malate, or only malate in watermelon (Seymour and McGlasson, 1993). Ethyl 2-methylbutanoate and methyl-2-methylpropanoate are among the most significant contributors to flavor of muskmelon cv. Makdimon, one of *C. mello reticulatus* cultivars which exhibit strong characteristic aromas. Muskmelon and watermelon also have cis-non-6-enal and cis, cis-nona-3,6,-dien-1-ol, respectively. The former has a strong melon-like aroma while the latter is reminiscent of watermelon rind. 4-Oxononanal and 2-hydroxy-5-pentyltetrahydrofuran have fruity and green odors and contribute to watermelon aroma. The volatile cis-non-6-enyl acetate has a pleasant honeydew melon-like aroma (Engle et al., 1990). Other varieties have ethyl 2-methylpropanoate, 2-methylbutyl acetate, 2-methylpropyl acetate and the thioether esters (Wyllie et al., 1995).

Tomato (*Lycopersicon esculentum*)
The SSC/TA ratio (De Bruyn et al., 1971), or content of SSC or TA are important for flavor (Stevens et

al., 1977; Jones and Scott, 1984). The major sugars are glucose and fructose in roughly equal amounts, while citrate and malate are the major organic acids, with citrate predominating (Baldwin et al., 1991a and b; Hobson and Grierson, 1993). However, over 400 volatile compounds were identified, of which 16 or so have odor thresholds that would indicate that they contribute to flavor (Buttery, 1993; Buttery and Ling, 1993). Of these, there is no clear odor impact compound. Buy, Buttery (1993) suggested that a combination of cis-3-hexenal, hexanal, 1-penten-3-one, 3-methylbutanal, trans-2-hexenal, 6-methyl-5-hepten-2-one, methyl salicylate, 2-isobutylthiazole, and β-ionone at the appropriate concentrations produces the aroma of a fresh ripe tomato. Of these, cis-3-hexenal and β-ionone have the highest odor units, and 2-isobutylthiazole is unique to tomato fruit. Furaneol has an odor threshold indicating that it might contribute to tomato flavor (Buttery et al., 1995). Volatile production occurs at the same time the ethylene climacteric and carotenoid synthesis/chlorophyll breakdown occur (Baldwin et al., 1991a). Enzymes important to tomato volatile synthesis from lipids include lipoxygenase, hydroperoxide lyase, a hydroperoxy cleavage, and alcohol dehydrogenase (Galliard, et al., 1977; Riley et al., 1996). Amino acid precursors include alanine, valine, leucine, isoleucine and phenylalanine (Buttery and Ling, 1993). Glycosides are also precursors to some volatiles (Krammer et al., 1994).

Conclusion: Flavor of fruits and vegetables is an important aspect of quality. Although difficult to define, qualify, and quantify, this elusive and complex trait is important to consumers and deserves more attention from both researchers and industry. Flavor quality of fresh and processed fruit and vegetable products will be an important factor in an increasingly competitive global market. Flavor maintenance becomes a challenge to maintain as shelf life and marketing distances increase due to new storage, handling and transport technologies. However, despite these issues, the bottom line for flavor quality is still genetic. Breeders need more information and analytical tools in order to select for flavor quality. Use of wild material may be necessary in breeding programs to regain flavor characteristics that have been lost from some commodities. Use of molecular markers that relate to flavor may help identify important enzymes in flavor pathways. The effect of harvest maturity on flavor quality needs to be determined for each commodity. With the current focus on flavor quality and current advances in flavor chemistry, sensory techniques and molecular biology, there are many opportunities to further efforts on behalf of flavor quality in fresh produce.

References:
Acree, T.E. 1993. Bioassays for flavor. In: T.E. Acree and R. Teranishi (eds) Flavor Science: Sensible Principles and Techniques, ACS Books, Wash. DC, pp. 1-20.
ASTM Standard Practice E679. 1991. Determination of odor and taste thresholds by a force choice ascending concentration series methods of limits, 1-5. Amer. Soc. Test. Materials, Philadelphia PA.
Baldwin, E.A., M.O. Nisperos, and M.G. Moshonas. 1991a. Quantitative analysis of flavor and other volatiles and for other constituents of two tomato varieties during ripening. J. Amer. Soc. Hort. Sci. 116:265-269.
Baldwin, E.A., M.O. Nisperos-Carriedo, and M.G. Moshonas. 1991b. Quantitative analysis of flavor parameters in six Florida tomato varieties (*Lycopersicon esculentum* Mill). J. Agric. Food Chem. 39:1135-1140.
Baldwin, E.A., M.O. Nisperos-Carriedo, and J.W. Scott. 1992. Levels of flavor volatiles in a normal cultivar, ripening inhibitor and their hybrid. Proc. Fla. State Hort. Soc. 104:86-89.
Baldwin, E.A., J.W. Scott, M.A. Einstein, T.M.M. Malundo, B.T. Carr, R.L. Shewfelt, and K.S. Tandon. 1998. Relationship between sensory and instrumental analysis for tomato flavor. J. Amer. Soc. Hort. Sci. 12:906-915.
Baldwin E.A., T.M.M. Malundo, R. Bender and J.K. Brecht. 1999a. Interactive effects of harvest maturity, controlled atmosphere and surface coatings on mango (*Mangifera indica* L.) flavor quality. HortScience 34:514.
Baldwin, E.A., J.K. Burns, W. Kazokas, J.K. Brecht, R.D. Hagenmaier, R.J. Bender, and E. Pesis. 1999b.

Effect of two edible coatings with different permeability characteristics on mango (*Mangifera indica* L.) ripening during storage. Postharv. Biol. Technol. 17:215-226.

Baldwin, E.A., J.W. Scott, C.K. Shewmaker, and W. Schuch. 2000. Flavor trivia and tomato aroma: biochemistry and possible mechanisms for control of important aroma components. HortScience 35:1013-1022.

Berger, R.G. 1991. Fruits. In: H. Maarse (ed) Volatile Compounds in Foods and Beverages, Marcel Dekker, NY, pp. 283-304.

Brady, C.J. 1993. Grape. In: G.B. Seymour, J.E. Taylor and G.A. Tucker (ed) Biochemistry of Fruit Ripening, Chapman and Hall, NY, pp. 379-404.

Bruemmer, J.H. 1975. Aroma substances of citrus fruits and their biogenesis. In: F. Drawart (ed) Symposium on Fragrance and Flavor Substances, Verlag Hans Carl., Nuremburg, Germany, pp. 167-176.

Buttery, R.G. 1993. Quantitative and sensory aspects of flavor of tomato and other vegetable and fruits. In: T.E. Acree and R. Teranishi (ed) Flavor Science: Sensible Principles and Techniques, ACS, Wash. DC, pp. 259-286.

Buttery, R.G. and L.C. Ling. 1993. Volatiles of tomato fruit and plant parts: Relationship and biogenesis. In: R. Teranishi, R. Buttery, and H. Sugisawa (ed) ACS Books, Wash. DC, pp. 23-34.

Buttery, R.G., G.R. Takeoka, and L.C. Ling. 1995. Furaneol: odor threshold and importance to tomato aroma. J. Agric. Food Chem. 43:1638-1640.

Cohen, E. Y. Shalom, and I. Rosenberger, I. 1990. Postharvest ethanol buildup and off-flavor in Murcott tangerine fruits. J. Amer. Soc. Hort. Sci. 115:775-778.

Cohen, R.A. and J.R. Hicks. 1986. Effect of storage on quality and sugars in muskmelon. J. Amer. Soc. Hort. Sci. 111:553-557.

Coombe, B.G. and M.G. McCarthy. 1997. Identification and naming of the inception of aroma development in ripening grape berries. Aust. J. Grape and Wine Res. 3:18-20.

Crouzet, J. P. Etievant, and C. Bayonove. 1990. Stone fruit: apricot, plum, peach, cherry. In: I.D. Morton and A.J. Macleod (eds) Food Flavors Part C, The Flavor of Fruits. Elsevier, NY, pp. 43-91.

Crouzet, J., A. Signoret, J. Coulibaly, and M.H. Roudsari. 1986. Influence of controlled atmosphere storage on tomato volatile components. In: G. Charalambous (ed) The Shelf Life of Foods and Beverages, Elsevier Science Publishers, Amsterdam, The Netherlands, pp. 355-367.

Cunningham, D.G., T.E. Acree, J. Barnard, R.M. Butts, P.A. Braell. 1985. Charm analysis of apple volatiles. Food Chem. 19:137-147.

Dan, K. S., Todoriki, M. Nagata, and I. Yamashita. 1997. Formation of volatile sulfur compounds in broccoli stored under anaerobic condition. J. Japan Soc. Hort. Sci. 65:867-875.

Demole, E., P. Enggist, and G. Ohloff. 1982. 1-p-Menthene-8-thiole: A powerful flavor impact constituent of grapefruit juice (*Citrus paradisi* Macfadyen) Helv. Chim. Acta 65:1785-1794.

DeRovira, D. 1997. Manual - Flavor nomenclature workshop: An odor description and sensory evaluation workshop. Flavor Dynamics, Inc., Somerset NJ.

De Bruyn, J.W., F. Garretsen, and E. Kooistra. 1971. Variation in taste and chemical composition of the tomato (*Lycopersicon esculentum* Mill). Euphytica 20:214-227.

Do, J.Y., D.K Salunkhe, and L.E. Olson. 1969. Isolation, identification and comparison of the volatiles of peach fruit as related to harvest maturity and artificial ripening. J. Food Sci. 34:618-621.

Dourtoglou, V., A. Gally, V. Tychopoulos, N. Yannovits, F. Bois, M. Alexandri, S. Malliou, M. Rissakis, and M. Bony. 1995. Effects of storage under CO2 atmosphere on the volatiles, phenylalanine ammonia-lyase activity and water soluble constituents of strawberry fruits. In: G. Charalamous (ed) Food Flavors: Generation, Analysis, and Process Influence, Elsevier Science, NY, pp. 1379-1394.

Eck, P. 1986. Blueberry. S.P. Monselise, ed. CRC Handbook of Fruit Set and Development, CRC Press, Boca Raton FL, pp. 75-85.

Engle, K.H. J. Heidlas, and R. Tressl. 1990. The flavour of tropical fruits (banana, melon, pineapple). In: I.D. Morton and J.D. MacLeod (eds) Food Flavors: Part C, The Flavor of Fruits, Elsevier Sci. Pub.,

Amsterdam, The Netherlands, pp. 195-219.

Fallik, E., D.D. Archbold, T.R. Hamilton-Kemp, J.H. Loughrin, and R.W. Collins. 1997. Heat treatment temporarily inhibits aroma volatile compound emission from Golden Delicious apples. J. Agric Food Chem. 45:4038-4041.

Fan, X. And J.P Mattheis. 1999. Impact of 1-methylcyclopropene and methyl jasmonate on apple volatile production. J. Agric. Food Chem. 47:2847-2853.

Fellman, J.K., J.P. Mattheis, M.E. Patterson, D.S. Mattinson, and B.C. Bostick. 1993. Study of ester biosynthesis in relation to harvest maturity and controlled-atmosphere storage of apples (*Malus domestica* Borkh.). Proc. 6th Intl. Contr. Atmos. Res. Conf., Cornell Univ. Ithaca NY.

Flora, L.F. and T.O.M. Nakayama. 1981. In: R. Teranishi and Harrera-Benitez (eds) Quality of Selected Fruits and Vegetables of North America, American Chemical Society, Wash. DC, pp. 21-27.

Galliard, T., J.A. Matthew, A.J. Wright, and M.J. Fishwick. 1977. The enzymic breakdown of lipids to volatile and non-volatile carbonyl fragments in disrupted tomato fruits. J. Sci. Food Agric. 28:863-868.

Georgilopoulos, D.N. and A.N. Gallois. 1987. Aroma compounds of fresh blackberries (*Rubus laciniata* L.). Z. Lebensm 'Unters' Forsch' 184:374-380.

Golaszewski, R., C.A. Sims, S.F. O'Keefe, R.J. Braddock, and R.C. Littell. 1998. Sensory attributes and volatile components of stored strawberry juice. J. Food Sci. 63:734-738.

Golding, J.B., D. Shearer, W.B. McGlasson, and S.G. Wyllie. 1999. Relationships between respiration, ethylene, and aroma production in ripening banana. J. Agric. Food Chem. 47:1646-1651.

Hartwig, P., and M. McDaniel. 1995. Flavor characteristics or lactic, malic, citric, and acetic acids at various pH levels. J. Food Sci. 60:384-388.

Hobson, G. And D. Grierson.1993. Tomato. In: G.B. Seymour, J.E. Taylor and G.A. Tucker (eds) Biochemistry of Fruit Ripening, Chapman and Hall, NY, pp. 405-442.

Honkanen, E. and T. Hirvi. 1990. The flavour of berries. In: I.D. Morton and J.D. MacLeod (eds) Food Flavors: Part C, The Flavor of Fruits, Elsevier Sci. Pub., Amsterdam, The Netherlands, pp. 125-193.

Honkanen, E., T. Pysalo, and T. Hirvi. 1980. The aroma of Finnish wild raspberries. Z. Lebensm. Unters. Forsch. 171:180-182.

Humpf, H.U. and P. Schreier. 1991. Bound aroma compounds from the fruit and the leaves of blackberry (*Rubus laciniata* L.). J. Agric. Food Chem. 39:1830-1832.

Jones, R.A., and S.J. Scott. 1984. Genetic potential to improve tomato flavor in commercial F1 hybrids. J. Amer. Soc. Hort. Sci. 109:318-321.

Kanellis, A.K. and K.A. Roubelakis-Angelakis. 1993. Grape. In: G.B. Seymour, J.E. Taylor and G.A. Tucker (ed) Biochemistry of Fruit Ripening, Chapman and Hall, NY, pp. 190-234.

Knee, M. 1993. Apple. In: G.B. Seymour, J.E. Taylor and G.A. Tucker (ed) Biochemistry of Fruit Ripening, Chapman and Hall, NY, pp. 325-346.

Koehler, P.E., and S.J. Kays. 1991. Sweet potato flavor: Quantitative and qualitative assessment of optimum sweetness. J. Food Qual. 14:241-249.

Krammer, G.E., G.R. Takeoka, and R.G. Buttery. 1994. Isolation and identification of 2,5-dimethyl-4-hydroxy-3(2H)-furanone glucoside from tomatoes. J. Agric. Food Chem. 42:1595-1597.

Larsen, M. and L. Poll. 1990. Odour thresholds of some important aroma compounds in raspberries. Z. Lebensm 'Unters' Forsch' 191:129-131.

Larsen, M., L. Poll, and C.E. Olsen. 1992. Evaluation of the aroma composition of some strawberry (*Fragaria ananassa* Duch) cultivars by use of odor threshold values. Z. Lebensm'Unters' Forsch' 195:536-539.

MacLeod, A.J. and N.G de Troconis. 1982. Volatile flavor components of mango fruit. Phytochemistry 21:2523-2526.

Malundo, T.M.M., R.L. Shewfelt, G.O. Ware, and E.A. Baldwin. 2001. Sugars and acids influence flavor properties of mango. J. Amer. Soc. Hort. Sci. 126:115-121.

Malundo, T.M.M., R.L. Shewfelt, G.O. Ware, and E.A. Baldwin. 2001. Alternative methods for

consumer testing and data analysis used to identify critical flavor properties of mango (*Mangifera indica* L.). J. Sens. Stud. 16:199-214.

Manning, K. 1993. Soft Fruit. In: G.B. Seymour, J.E. Taylor and G.A. Tucker (eds) Biochemistry of Fruit Ripening, Chapman and Hall, NY, pp. 347-377.

Martens, M., E. Risvik, and H. Martens. 1994. Matching sensory and instrumental analyses. In: J.R. Piggott and A. Paterson (eds) Understanding Natural Flavors, Blackie Acad. Professional/Chapman and Hall, Gasgow UK, pp. 60-76.

Mattheis, J.P., D.A. Buchanan, and J.K. Fellman. 1995. Volatile compound production by Bisbee Delicious apples after sequential atmosphere storage. J. Agric. Food Chem. 43:194-199.

Maul, F., S.A. Sargent, M.O. Balaban, E.A. Baldwin, D.J. Huber, and C.A. Sims. 1998. Aroma volatile profiles from ripe tomatoes are influenced by physiological maturity at harvest: an application for electronic nose technology. J. Amer. Soc. Hort. Sci. 123:1094-1101.

Maul, F., S.A. Sargent, C.A. Sims, E.A. Baldwin, M.O. Balaban and D.J. Huber. 2000. Recommended storage temperatures affect tomato flavor and aroma quality. J. Food Sci. 65:1228-1237.

McDonald, R.E., T.G. McCollum, and E.A. Baldwin. 1996. Prestorage heat treatments influence free sterols and flavor volatiles of tomatoes stored at chilling temperature. J. Amer. Soc. Hort. Sci. 12:531-536.

Marton, I.D. and A.J. MacLeod. 1990. Food Flavors: Part C. The Flavor of Fruits. Elsevier Science, NY.

Moshonas, M.G. and P.E. Shaw. 1972. Analysis of volatile flavor constituents from tangerine essence. J. Agric. Food Chem. 20:70-71.

Moshonas, M.G. and P.E. Shaw. 1997. Dynamic headspace gas chromatography combined with multivariate analysis to classify fresh and processed orange juices. J. Ess. Oil Res. 9:133-139.

Narain, N., P.S. Bora, R. Narain, and P.E. Shaw. 1997. Quantitative determination of 46 volatile constituents in fresh, unpasteurized orange juices using dynamic headspace gas chromatography. In: P. Shaw, H. Chan, and S. Nagy (eds) Tropical and Subtropical Fruits, Vol. 1, AgScience, Auburndale FL, pp. 1-77.

O'Mahony, M. 1995. Sensory measurement in food science: fitting methods to goals. Food Tech. Apr:72-82.

Park, S.K., J.C. Morrison, D.O. Adams, and A.C. Noble. 1991. Distribution of free and glycosidically bound monoterpenes in the skin and mesocarp of Muscat of Alexandria grapes during development. J. Agric. Food Chem. 39:514-518.

Paterson, A., J.R. Piggott, and J. Jiang. 1993. Approaches to mapping loci that influence flavor quality in raspberries. In: Food Flavor and Safety Molecular Analyses and Design. ACS Symp. Ser. 528:109-117.

Paz, O. H.W. Janes, B.A. Prevost, and C. Frenkel. 1981. Enhancement of fruit sensory quality by postharvest applications of acetaldehyde and ethanol. J. Food Sci. 47:270-276.

Perez, A.G., A. Cert, J.J. Rios, and J.M. Olias. 1997. Free and glycosidically bound volatile compounds from two banana cultivars: Valery and Pequena Enana. J. Agric. Food Chem. 45:4393-4397.

Perez, A.G., C. Sanz, R. Olias, and J.M. Olais. 1999. Lipoxygenase and hydroperoxide lyase activities in ripening strawberry fruits. J. Agric. Food Chem. 47:249-253.

Peters. A. M. and A. Van Amerongen. 1998. Relationship between levels of sesquiterpene lactones in chicory and sensory evaluation. J. Amer. Soc. Hort. Sci. 123:326-329.

Podoski, B.W., C.A. Sims, S.A. Sargent, J.F. Price, C.K. Chandler, and S.F. Okeefe. 1997. Effects of cultivar, modified atmosphere, and pre-harvest conditions on strawberry quality. Proc. Fla. State Hort. Soc. 110:246-252.

Riley, J.C. M., C. Willemot, and J.E. Thompson. 1996. Lipoxygenase and hydroperoxide lyase activities in ripening tomato fruit. Postharv. Biol. Technol. 7:97-107.

Robbins, J.A. and J.K. Fellman. 1993. Postharvest physiology, storage and handling of red raspberry. Postharv. News Info. 4:53-59.

Roberts, D.D. and T.E. Acree. 1996. Effects of heating and cream addition on fresh raspberry aroma

using a retronasal aroma simulator and gas chromatography olfactometry. J. Agric. Food Chem. 44:3919-3925.

Romani, R., J. Labavitch, T. Yamashita, B. Hess, and H. Rae. 1983. Preharvest AVG treatment of 'Bartlett' pear fruit: Effects on ripening, color change, and volatiles. J. Amer. Soc. Hort. Sci. 108:1046-1049.

Roscher, R., P. Schreier, and W. Schwab. 1997. Metabolism of 2,5-dimethyl-4-hydroxy-3(2H)-furanone in detached ripening strawberry fruits. J. Agric. Food Chem. 45:3202-3205.

Saftner, R.A., W.S. Conway, and C.E. Sams. 1999. Postharvest calcium infiltration alone and combined with surface coating treatments influence volatile levels, respiration, ethylene production, and internal atmospheres of 'Golden Delicious' apples. J. Amer. Soc. Hort. Sci. 124:553-558.

Salunkhe, D.K. and B. Desai. 1984. Postharvest Biotechnology of Fruits. Vol II. CRC Press, Boca Raton FL.

Schaller, E., J.O. Bosset, and F. Escher. 1998. 'Electronic noses' and their application to food. Lebens. - Wiss Technol. 31:305-316.

Schamp, N. and P. Dirinck. 1982. The use of headspace concentration on Tenax for objective evaluation of fresh fruits. In: G. Charalambous (ed) Chemistry of Foods and Beverages, Acad. Press, NY, pp. 25-47.

Seymour, G.B. 1993. Banana. In: G.B. Seymour, J.E. Taylor and G.A. Tucker (eds) Biochemistry of Fruit Ripening, Chapman and Hall NY, pp. 83-106.

Seymour, G.B. and W.B. McGlasson. 1993. Melons. In: G.B. Seymour, J.E. Taylor and G.A. Tucker (eds) Biochemistry of Fruit Ripening, Chapman and Hall NY, pp. 273-290.

Shamaila, M. W.D. Powrie, and B.J. Skura. 1992. Analysis of volatile compounds from strawberry fruit stored under modified atmosphere packaging (MAP). J. Food Sci. 57:1173-1176.

Shaw, P.E. 1991. Fruits II. In: H. Maarse (ed) Volatile Compounds in Foods and Beverages. Marcel Dekker, NY.

Shaw, P.E. and C.W. Wilson. 1980. Importance of selected volatile components to natural orange, grapefruit, tangerine, and mandarin flavors. In. S. Nagy and J.A. Attaway (eds) Citrus Nutrition and Quality, ACS Symp. Ser. No. 143, American Chemical Society, Wash. DC, pp. 167-190.

Shukor, A.R., A. Faridah, H. Abdullah, and Y.K. Chan. 1998. Pineapple. In: P.E. Shaw, H.T. Chan, and S. Nagy (eds) Tropical and Subtropical Fruits, Vol 1, AgScience, Auburndale FL, pp. 137-190.

Shure, K.B. and T.E. Acree. 1995. In vivo and in vitro flavor studies of *Vitis labruscana* cv. Concord. In: R.L. Rouseff and M.M. Leahy (eds) Fruit Flavors: Biogenesis, Characterization, and Authentication, American Chemical Society, Wash. DC, pp. 127-133.

Song, J., B.D. Gardner, J.F. Holland, and R. M. Beaudry. 1997. Rapid analysis of volatile flavor compounds in apple fruit using SPME and GC/time of flight spectrometry. J. Agric. Food Chem. 45:1801-1807.

Speirs, J. E. Lee, K. Holt, K. Young-Duk, N. S. Scott, B. Loveys, and W. Schuch. 1998. Genetic manipulation of alcohol dehydrogenase levels in ripening tomato fruit affects the balance of some flavor aldehydes and alcohols. Plant Physiol. 117:1047-1058.

Stevens M.A., A.A. Kader, M. Albright-Holton, and M. Algazi. 1977. Genotypic variation of flavor and composition in fresh market tomatoes. J. Amer. Soc. Hort. Sci. 102:680-689.

Tandon, K.S., E.A. Baldwin, and R.L. Shewfelt. 2000. Aroma perception of individual volatile compounds in fresh tomatoes (*Lycopersicon esculentum* Mill.) As affected by the medium of evaluation. Postharvest Biol. Technol. 20:261-268.

Taylor, J.E. 1993. Exotics. In: G.B. Seymour, J.E. Taylor, and T.A. Tucker (ed) Biochemistry of Fruit Ripening, Chapman and Hall, London UK, pp. 151-187.

Teranishi, R. and S. Kint. 1993. Sample preparation. T. Acree and R. Teranshi (ed) Flavor Science: Sensible Principles and Techniques, ACS Books, Wash. DC, pp. 137-167.

Webb, A.D. 1981. Quality factors in California grapes. In: R. Teranishi and Harrera-Benitez (ed) Quality of Selected Fruits and Vegetables of North America. American Chemical Society, Wash. DC, pp. 1-

9.

Wilson, C.W., P.E. Shaw, and R.J. Knight. 1986. Importance of selected volatile compounds to mango (*Mangifera indica* L.) flavor. In: R.M. Lawrence, B.D. Mookherjee, and B.J. Willis (eds) Flavors and Fragrances: A World Perspective, Proc. 10th Intl Cong. Essential Oils, Fragrances and Flavors, Wash. DC, pp. 283-294.

Wright, D.H. and N.D. Harris. 1985. Effect of nitrogen and potassium fertilization on tomato flavor. J. Agric. Food Chem. 33:355-358.

Wyllie, S.G., D.N. Leach, Y. Wang and R.L. Shewfelt. 1995. Key aroma compounds in melons: Their development and cultivar dependence. In: American Chemical Society Symp Ser. 596:248-257.

Young, H., J.M. Gilbert, S.H. Murray, and R.D. Ball. 1996. Causal effects of aroma compounds on Royal Gala apple flavors. J. Sci. Food Agric. 71:329-326.

Zabetakis, I. and M.A. Holden. 1997. Strawberry flavor: Analysis and biosynthesis. J. Sci. Food Agric. 74:421-434.

Table 1. Odor descriptors for tomato aroma compounds in deionized water, ethanol/methanol/deionized water mix and deodorized tomato homogenate (Tandon et al., 2000).

Aroma compound	Deionized water	EtOH/MeOH/water	Tomato homogenate
hexanal	grassy/green	rancid/stale oil	stale/green/grassy
trans-2-hexenal	floral/grass/apple	fruity/almond/vine	stale/green/vine
cis-3-hexenol	leafy/cut grass	freshcut grass	green/celery
hexanol	mint/grass	alcohol	glue/oil
6-methyl-5-hepten-2-one	raw greens/nutty	alcohol/paint	sweet/floral
cis-3-hexenal	grass/tomato-like	alcohol/paint	tomato/citrus
2-isobutylthiazole	fermented/plastic	alcohol/tomato-like	pungent/bitter
2-pentenal	vine/organic solvent	acetone/medicine	stale/oil
acetone	glue/alcohol	alcohol/nutty/spoilt	green
β-ionone	sweet/perfume-like	sweet	sweet/floral
geranylacetone	sweet/paint/sharp	sweet/floral/leafy	sweet/citrus/ester
3-methylbutanol	earthy/watermelon rind	glue/mint/cinnamon	sweet/fresh
phenylethanol	floral/roses	alcohol	alcohol/nutty
3-methylbutanal	bug spray/alcohol	fruity/green/leafy	stale/rotten
1-penten-3-one	glue/oil/pungent	nutty/glue/alcohol	fresh/sweet
ethanol	earthy/stale	pungent/rancid	
methanol	earthy/stale		

Table 2. Some important or abundant flavor compounds in selected fruits and vegetables.

Fruit	Major sugars	Major acids	Important aroma compounds
Apple Fellman et al., 1993 Honkanen and Hirvi, 1990 Knee, 1993 Mattheis et al., 1995 Young et al., 1996	sucrose glucose fructose	malic citric	β-damascenone butyl hexanoate isoamyl hexanoate hexyl hexanoate ethyl butanoate propyl butanoate hexyl butanoate butylacetate 2-ethyl-1-butyl acetate ethyl acetate butanol
Peach Brady, 1993 Crouzet et al., 1990 Do et al., 1969	sucrose glucose fructose sorbitol	malic citric	benzaldehyde benzyl alcohol nonanol linalool ethyl hexanoate 3-methylbutanoate α-terpineol γ-hexalactone δ-decalactone γ-undecalactone δ-undecalactone γ-dodecalactone δ-dodecalactone α-pyrone 6-pentyl-α-pyrone
Strawberry Golaszewski et al., 1998 Honkanen et al., 1980 Manning, 1993 Perez et al.,1999 Roscher et al., 1997 Zabetakis and Holden, 1997	sucrose, glucose, fructose	citric	hexanal *cis*-3-hexanal *trans*-2-hexanal furaneol mesifuran ethyl hexanoate ethyl butanoate methyl butanoate ethyl-2-methyl propanoate
Raspberry Dourtoglou et al., 1995 Honkanen and Hirvi, 1990 Larsen and Poll, 1990; Larsen et al., 1992 Paterson et al., 1993 Robbins and Fellman, 1993	sucrose glucose fructose	citric	H-(4-Hydroxyphenyl-butan-2-one) (raspberry ketone) α-ionone β-ionone geraniollinalool benzyl alcohol ethyl hexanoate ethyl butanoate

Roberts and Acree, 1996			methyl butanoate γ-decalactone 2-heptanone *cis*-3-hexanal β-damascenone
Grape Concord (*Vitis labruscana*) Muscadine *V. rotundifolia* (References for all grape types) Coombe and McCarthy, 1997 Flora and Nakayama, 1981 Kanellis and Roubelakis- Angelakis, 1993 Park et al.,1991 Shure and Acree, 1995 Webb, 1981 Muscat varieties (*V. vinifera*)	glucose fructose	tartaric malic	methyl anthranilate 0-aminoacetophenone furaneol methyl furaneol β-damascenone β-phenylethanol butyl alcohol hexyl alcohol hexanal *trans*-2-hexenal isoamyl alcohol acetaldehyde isobutyraldehyde ethyl acetate ethyl propionate butyl acetate propyl acetate 2-methylbutanol linalool geraniol methoxyisobutylpyrazine
Banana Berger, 1991 Engel et al., 1990 Perez et al., 1997 Seymour, 1993	sucrose glucose fructose	malic citric oxalic	decan-1-ol 2-phenylethanol 3-oxy-pentanoic acid 3-methylbutanoic acid 3-methylbutyl acetate butanoate 3-methylbutanoate eugenol 5-methoxyeugenol eugenol-methylether elemicin
Sweet Orange Bruemmer 1975 Shaw 1991 Shaw and Wilson 1980	sucrose glucose fructose	citric	geranial neral acetaldehyde decanal octanal nonanal ethyl acetate ethyl propionate ethyl butanoate methyl butanoate

			ethyl-2-methyl butanoate ethyl-3-hydroxy hexanoate linalool α-terpineol limonene myrcene α-pinene valencene
Tangerine Moshonas and Shaw, 1972 Shaw and Wilson, 1980	sucrose glucose fructose	citric	acetaldehyde decanal octanal dimethyl anthranilate thymol α-sinensal γ-terpinene β-pinene
Grapefruit Demole et al., 1982 Shaw and Wilson, 1980	sucrose glucose fructose	citric	acetaldehyde decanal ethyl acetate methyl butanoate ethyl butanoate 1-*p*-menthene-8-thiol nootkatone limonene naringin
Mango Baldwin et al., 1999 MacLeod and de Troconis, 1982 Nairain et al., 1997 Wilson et al., 1986	sucrose glucose fructose	citric malic	ethyl butanoate ethyl-2-butanoate hexanal cis-3-hexanal trans-2-hexanal γ-octalactone γ-dodecalactone furaneol α-pinene β-pinene 3-carene myrcenelimonene *p*-cymene terpinolene α-Copaene caryophyllene
Melon: Cantaloupe Honeydew Watermelon Engle et al., 1990 Seymour and McGlasson, 1993	sucrose fructose	malic citric watermelon - malic only	ethylbutyrate ethyl-2-methyl butyrate ethyl butyrate ethyl hexanoate hexyl acetate 3-methylbutyl acetate benzyl acetate

Wyllie et al., 1995			*cis*-6-nonenyl acetate *trans*-6-nonenol *cis*, *cis* -3,6-nonadienol *cis*-6-nonenal 4-oxononanal 2-hydroxy-5-pentyltetra-hydrofuran *cis*-non-6-enyl acetate methyl acetate ethyl acetate isopropyl acetate ethyl propanoate ethyl isobutanoate propyl acetate butyl acetate methyl-2-methylbutanoate ethyl butanoate 2-methylpropanoate 2-methylbutyl acetate 2-methylpropyl acetate methyl (methylthio) acetate ethyl (methylthio) acetate ethyl (methylthio)propanoate
Tomato Baldwin et al.,1991ab Buttery 1993 Buttery and Ling 1993 Buttery et al. 1995, 1989 De Bruyn et al. 1971 Hobson and Grierson 1993	glucose fructose	citric malic	hexanal *trans*-2-hexenal *cis*-3-hexenal *cis*-3-hexenol β-ionone β-damascenone 1-penten-3-one 3-methylbutanal 3-methylbutanol 2-isobutylthiazole1-nitro-phenyl-ethane *trans*-2-heptenal phenylacetaldehyde 6-methyl-5-hepten-2-one methyl salicylate geranylacetone